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Specification and Drawings as originally filed, with Application for Patent Serial No: **2,326,362**, on November 20, 2000, by **JDS UNIPHASE INC.**, assignee of Thomas Ducellier, Rajiv Iyer and Andrew Tsiboulia, for "Optical Switch ".

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Abstract

The invention provides an optical switch having an input port for launching a beam of light into the optical switch; a plurality of output ports, each output port for selectively receiving the beam of light; an element having optical power and a focal length approximately equal to a near zone length or the Raleigh range for providing an angle to offset transformation; and beam directing means for selectively directing the beam of light from the input port to any one of the plurality of output ports along an optical path via the element having optical power. The element having optical power is a lens or a curved mirror.

OPTICAL SWITCH

Field of the Invention

The present invention relates generally to optical switches and in particular to an optical switch based on the angles to offset principle.

Background of the Invention

Optical matrix switches are commonly used in communications systems for transmitting voice, video and data signals. Generally, optical matrix switches include multiple input and/or output ports and have the ability to connect, for purposes of signal transfer, any input port/output port combination, and preferably, for N x M switching applications, to allow for multiple connections at one time. At each port, optical signals are transmitted and/or received via an end of an optical waveguide. The waveguide ends of the input and output ports are optically connected across a switch interface. In this regard, for example, the input and output waveguide ends can be physically located on opposite sides of a switch interface for direct or folded optical pathway communication therebetween, in side-by-side matrices on the same physical side of a switch interface facing a mirror, or they can be interspersed in a single matrix arrangement facing a mirror.

Establishing a connection between a given input port and a given output port, involves configuring an optical pathway across the switch interface between the input ports and the output ports. One way to configure the optical pathway is by moving or bending optical fibers using, for example, piezoelectric benders. The benders associated with fibers to be connected bend the fibers so that signals from the fibers are targeted at one another so as to form the desired optical connection across the switch interface. The amount of bending is controlled based on the electrical signal applied to the benders. By appropriate arrangement of benders, two-dimensional targeting control can be effected. Another way of configuring the optical path between an input port and an output port

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involves the use of one or more moveable mirrors interposed between the input and output ports. In this case, the waveguide ends remain stationary and the mirrors are used for switching. The mirrors can allow for two-dimensional targeting to optically connect any of the input port fibers to any of the output port fibers.

An important consideration in switch design is minimizing switch size for a given number of input and output ports that are serviced, i.e., increasing the packing density of ports and beam directing units. It has been recognized that greater packing density can be achieved, particularly in the case of a movable mirror-based beam directing unit, by folding the optical path between the fiber and the movable mirror and/or between the movable mirror and the switch interface. Such a compact optical matrix switch is disclosed in U.S. Patent No. 6,097,860. In addition, further compactness advantages are achieved therein by positioning control signal sources outside of the fiber array and, preferably, at positions within the folded optical path selected to reduce the required size of the optics path.

Current switch design continuously endeavors to accommodate more fibers in smaller switches.

However, the current approach for optical switching is to attach an individual lens collimator to each individual input and output port in order to "throw" the beam to the switching element and to the desired output port. For an N x M switch with a high port count, this is a time consuming and costly procedure. In accordance with the present invention it is advantageous to move away from the traditional "beam-throwing" approach and move towards geometric and imaging optics, where a single element having optical power, such as a mirror or a lens or lens system, is used to image the entire input waveguide array to the switching system, which is then in turn imaged to the output waveguide array.

It is an object of this invention to provide a compact optical switch, modulator, and/or attenuator.

Summary of the Invention

In accordance with the invention there is provided an optical switch comprising an input port for launching a beam of light into the optical switch; a plurality of output ports, each output port for selectively receiving the beam of light; an element having optical power and a focal length approximately equal to a near zone length for providing an angle to offset transformation; and beam directing means for selectively directing the beam of light from the input port to any one of the plurality of output ports along an optical path via the element having optical power.

In accordance with the invention, there is further provided an optical switch comprising an input port for launching a beam of light into the optical switch; a plurality of output ports, each output port for selectively receiving the beam of light; an element having optical power and a focal length approximately equal to a Raleigh range for providing an angle to offset transformation; and beam directing means for selectively directing the beam of light from the input port to any one of the plurality of output ports along an optical path via the element having optical power. The element having optical power is a lens or a curved mirror.

In accordance with another aspect of the invention, there is provided, an optical switch comprising an array of controllable deflecting elements for deflecting a beam of light and an optical element having power optically coupled with the array of deflecting elements whose focal length is approximately equal to the Raleigh range of the beam being deflected.

In accordance with the invention a compact optical switch is provided. The optical switch comprises an element having optical power with a focal length approximately equal to the near zone length or Raleigh range.

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In accordance with the present invention there is further provided a modulator or attenuator comprising an element having optical power with a focal length approximately equal to the near zone length or Raleigh range.

Brief Description of the Drawings

Exemplary embodiments of the invention will now be described in conjunction with the drawings in which:

Fig. 1 shows a prior art optical switch wherein the beam of each input waveguide is individually collimated;

Fig. 2 describes the ATO principle through geometric optics by means of an Angle-To-Offset Link Lens (ATOLL);

Fig. 3 shows a basic optical system for an optical switch in accordance with the present invention based on an Angle-to-Offset Mirror (ATOM);

Fig. 3a shows an example of the basic optical system presented in Fig. 3 having a dual mirror arrangement as beam directing means;

Fig. 3b shows another example of the basic optical system presented in Fig. 3 having a different dual mirror arrangement as beam directing means;

Fig. 3c shows an example of a compact 1024x1024 optical switch in accordance with the invention;

Fig. 3d presents Fig. 19 of U.S. Patent No. 6,101,299;

Fig. 4 shows beam directing means in form of a MEMS device;

Fig. 5 shows an optical switch in a transmissive configuration in accordance with the invention based on an ATOLL and MEMS chips;

Fig. 6 shows an optical switch in accordance with the invention based on an ATOM and a MEMS chip;

Fig. 7 is a schematic presentation of a drawn fiber bundle for increasing the filling factor;

Fig. 8 is a graphic presentation of the filling factor and mode diameter dependence on the drawing factor;

Fig. 9 shows a mirror ATO system with parallel projecting;

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Fig. 10 is a schematic presentation of superimposing four honeycomb structures on each other; and

Fig. 11 shows an alternative optical system in accordance with the invention having an off-axis telecentric imaging system.

Detailed Description of the Preferred Embodiments

Turning now to Fig. 1 a prior art optical switch or cross-connect structure 100 is shown, wherein micro-mirrors 110 on a MEMS chip 112 are used to fold the design. The folded optical pathway configuration allows for a compact switch design using the movable mirror based beam directing unit. However, the general approach in prior art optical cross connectors is to individually collimate each input waveguide and direct the beam to its dedicated mirror. This mirror then deflects this beam to any one of the plurality of output mirrors which then redirects the beam, i.e. compensates for the angle, to its dedicated output waveguide. As is seen from Fig. 1, this design requires the use of a lens 114 for each individual input fiber of input fiber bundle 116 and each individual output fiber of output fiber bundle 118.

Traditional switching optics do not convert angles to offsets in the image plane but rather convert them back into angles, and based on the optical imaging system used with a certain magnification. In accordance with the present invention a new optical switching system is used that is optically separated from the imaging system. This does not only create the angles to offsets transformation (ATO transformation) but also maintains the beam size so that the translated image is further imaged to the output waveguides at the output ports. This is explained in more detail below in conjunction with the explanation of the ATO principle. The ATO principle can be described in terms of Geometric Optics or in terms of Gaussian Beam Optics.

ATO Principle Described Through Geometric Optics

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Fig. 2 explains the ATO principle through geometric optics by means of an Angle-to-Offset Link Lens (ATOLL). Fig. 2 shows an array of N light beams with their waists situated at plane 1. This array occupies a circle with a radius R_a. Each of these beams has the waist beam radius R_b and semi-divergence angle θ. The length of the near-zone of all these beams is $Z_n = R_b / \theta$. In accordance with the present invention, any one of these beams is to be directed to any point within a circular area with a radius R_a in plane 2. Further, in accordance with the invention, all of these beams have their waists at plane 2, having the same beam radius R_b and the same semi-divergence angle θ. Plane 1 is the front focal plane of the ATOLL 202, and plane 2 is its rear focal plane. The effective (rear) focal length of the lens f' is equal to Z_n, the length of the near zone of all the light beams.

The beam waist radius at plane 2 is equal $R_b' = \theta f' = \theta Z_n = R_b$. The beam semi-divergence angle after the lens is $\theta' = R_b / f' = R_b / Z_n = \theta$. Thus, the beam waist radius and divergence remain the same after the lens. The position of the beam axis at plane 2 is equal to $h' = -\sigma f'$, where σ is the beam axis tilt angle at plane 1. It is defined entirely by this angle, and hence by steering this angle at plane 1 within the range $\Delta\sigma_b = \pm R_a / Z_n$, a beam is directed to any point at plane 2 within a circle of radius R_a.

The diameter of the ATOLL 202 is chosen to be not less than $D_A = 2R_a + 2\Delta\sigma f' + 2\theta f'$.

This description applies to both, multi-mode and single-mode fiber light beams. The semi-divergence angle of a single-mode light beam is equal to $\theta = \lambda / \pi \omega_b$ The near zone of a single-mode light beam is called Raleigh range and is equal to $Z_n = \pi \omega_b^2 / \lambda$, where ω_b is the single-mode beam waist radius defined at the $1/e^2$ energy level and λ is the wavelength.

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ATO Principle Described Through Gaussian Beam Optics

The beam power of a Gaussian beam is principally concentrated within a small cylinder surrounding the beam axis. The intensity distribution in any transverse plane is described by a circularly symmetric Gaussian function centered about the beam axis. The width of this function is at a minimum at the beam waist and grows gradually in both directions. Within any transverse plane, the beam intensity assumes its peak value on the beam axis and drops by the factor $1/e^2$ at the radial distance $\rho = W(z)$. $W(z)$ is regarded as the beam radius or the beam width, since about 86% of the beam power is carried within a circle of this radius $W(z)$. The dependence of the beam radius on z is described by the following equation:

$$W(z) = W_0\left[1+\left(\frac{z}{z_0}\right)^2\right]^{1/2}$$

The beam radius assumes its minimum value W_0 in the plane $z = 0$ which is called the beam waist, and hence W_0 is the waist radius. The beam radius increases gradually with z, reaching $\sqrt{2}W_0$ at $z = z_0$, and continues increasing monotonically with z. If $z \gg z_0$ then the first term can be neglected resulting in the following linear relation

$$W(z) \approx \frac{W_0}{z_0} z = \theta_0 z$$

wherein $\theta_0 = W_0 / z_0$,

using $W_0 = \left(\frac{\lambda\ z_0}{\pi}\right)^{1/2}$,

the following equation is obtained

$$\theta_0 = \frac{\lambda}{\pi\ W_0}.$$

Further, if $z \gg z_0$, i.e. far from the beam center, the beam radius increases approximately linearly with z, defining a cone with half angle θ_0. About 86% of the beam power is confined within this cone. The angular divergence of the beam is therefore defined by the divergence angle

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$$\theta_0 = \frac{2}{\pi} \frac{\lambda}{2W_0}.$$

As is seen, the beam divergence is directly proportional to the ratio between the wavelength λ and the beam waist diameter $2W_0$.

The parameter z_0 is known as the Raleigh range or near zone and denotes a distance where the area of the beam doubles. Thus,

if $$A_1 = 2A_0$$

and $$A_1 = \pi W_1^2 \text{ and } A_0 = \pi W_0^2$$

$$\pi W_1^2 = 2\pi W_0^2$$

$$W_1 = \sqrt{2} W_0$$

General Gaussian beam theory states that if the input waist of $1/e^2$ beam radius W_1 is placed at the front focal plane of a lens of focal length F then the output waist of $1/e^2$ beam radius W_2 is located at the back focal plane of the lens. The relationship between these radius sizes is shown in the following equation

$$W_2 = \frac{F\lambda}{\pi W_1}$$

It is apparent from this equation, that the input beam size and divergence equals the output beam size for a given focal length F. Thus, for a given focal length of the lens, the focal length is proportional to the square of the beam radius. This applies also in an analogous manner to a mirror, another element having optical power, where the front and back focal plane are the same.

Fig. 3 presents a basic optical system for an optical switch 200 in accordance with the present invention based on an Angle-to-Offset Mirror (ATOM) 210. A waveguide bundle 220 is shown on the left of Fig. 3 with arrowheads denoting respective interleaved input and output ports of the switch 200. Beam directing means 230 are provided using a

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transmissive deflection mechanism in order to direct the beam to a certain point of the ATOM 210 so that the beam is deflected to a respective output port of waveguide bundle 220. The beam directing means 230 are described in more detail below. It is apparent, that the beam can be directed to any one of the output ports of waveguide bundle 220 by appropriately selecting the deflection point on ATOM 210. In accordance with the present invention, ATOM 210 has a focal length L 240 corresponding to the near zone length or Raleigh range. Such an arrangement provides a compact optical system in which the necessary deflection angles are reduced by two and further avoids excess losses due to a defocusing. In order to determine the switch dimensions the following scaling factors are used: an F# of the ATOM 210, an area filling factor for micro-beams (K), and a linear number of ports (N); for example N=64 for a 4096x4096 optical switch. The dimensions of the optical switch 200 are determined by the diameter (ϕ) 244 of the ATOM 210

$$\phi = \frac{L}{F\#},$$

the divergence angle (θ) 246

$$\tan(\theta) = \frac{1}{4F\#},$$

the diameter (d) 242 of the waveguide bundle 220

$$d = \frac{18(2N-1)^2\lambda}{K\pi}F\#, \text{ and}$$

the focal length (L) 240 of the ATOM 210

$$L = \frac{36(2N-1)^2\lambda}{K\pi}F\#^2.$$

The deflection mechanism of beam directing means 230 can be an arrangement of dual mirrors or an arrangement of a wedge on a dual tilt mount. Fig. 19 of U.S. Patent No. 6,101,299 illustrates such means for bi-directionally directing the beam of light from the input waveguides to the ATOM and from the ATOM to the output waveguides. Such dual mirror arrangements are for example a combination of a first mirror operable in horizontal deflection and a second mirror operable in vertical deflection, e.g. Fig. 3a, or a

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combination of a fixed mirror as a first mirror and a second mirror that is operable in 2D deflection, e.g. Fig. 3b.

Alternatively, a MEMS device 300, such as shown in Fig. 4, can be used as a transmissive deflector. This MEMS device 300 changes an axis of an optical cone of a beam of light emitted by the waveguide but keeps its "vertex" in place. This change is indicated by dotted lines in Fig. 4 and by repositioning the waveguide 312 from position A to position B, the axis of the optical cone changes from 310a to 310b, respectively. Waveguide 312 is placed into a small countersunk bearing hole 314 of a top chip 316 (Si wafer 250 μ) of MEMS device 300. The bottom chip 318 (Si wafer 250 μ) is bonded to the top chip 316 with solder bumps 320 (30 μ), which can give interwafer distances controllable to submicron accuracy. The waveguide 312 passes through a hole in this wafer/bottom chip 318, and is engaged by an x-y positioner 322, such as a comb drive or a thermal drive. In order to apply a larger force on waveguide 312, two comb drives or two thermal drives are provided. The waveguide continues for some distance to a strain relief fixture 324, to avoid a possible fracture of the waveguide for example. The required actuation for a +/- 7 degree steering with the dimensions shown in Fig. 4 is about +/- 35 to 40 μ.

Fig. 5 shows another embodiment of the present invention wherein the optical switch 500, drawn in a transmissive configuration, is based on an Angle-To-Offset Link Lens (ATOLL) as the element of optical power and two MEMS chips. Switch 500 has an input waveguide bundle 510 and output waveguide bundle 512, imaging lenses 514, an input MEMS chip 516 and an output MEMS chip 518, and an ATOLL 520. The description presented herein only discusses the light issued from the input bundle 510, i.e. the input side of the system 500. Since this is a symmetric system and since light is generally bi-directional, the description also applies to the output side.

Each fiber end-face is imaged onto a respective micro-mirror on the MEMS chip 516 using imaging lens 514. The focal length f_a of the ATOLL 520 is equal to the near-zone length (multimode fibers) or the Raleigh range (single mode fibers) of the beam at the

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MEMS plane and thus, the MEMS chips 516 and 518 are placed at the front and back focal planes of the ATOLL 520, as shown in Fig. 5. By properly directing two micro-mirrors of the two MEMS chips 516 and 518, a link between any two waveguides from the input waveguide bundle 510 to the output waveguide bundle 512 is established. Thus, the MEMS chips 516 and 518 fulfil the function of beam directing means. The micro-mirrors on the MEMS chip 516 introduce a tilt of each input beam which is converted to a lateral displacement with the same mode size through the ATOLL onto a set of output micro-mirrors on the second MEMS chip 518 which redirect these beams to a the outputs at the output waveguide bundle 512. The range of the mirror steering is one-half the range of the beam steering as shown in the following equation, see also the section describing the ATO principle through geometric optics,

$$\Delta\sigma_b = \pm R_a / 2 Z_n .$$

The beam axes between the input waveguide bundle 510 and imaging lens 514 are parallel to each other, or telecentric; however, they cease to be telecentric as they propagate from the imaging lens 514 to the MEMS chip 516. The skew angle of the beam axis after lens 514 is $\sigma' = h / f'$, where h is one-half of the size of the waveguide bundle, or expressed alternatively, the height of the fiber bundle from the optical axis. Therefore, the skew angle needs to be compensated by non-uniform tilting of each micro-mirror on the MEMS chip 516 which results in an increase of the required angle of mirror steering. However, it is desirable to minimize the total required angle of micro-mirror deflection, and in accordance with a further embodiment of the present invention a second magnifying system is included in order to image the beams from the MEMS chip to the ATO lens. The use of a second magnifying lens provides additional room, if needed, and magnification to increase the mode size in the case that the focal length of the ATO lens 520 is too small. However, it is advantageous to replace lenses 514 with a telecentric 4-f relay magnifier. Replacing lenses 514 by telecentric systems of the same magnification ensures a telecentricity of the beam axes as they approach the MEMS chip which obviates an increase in the range of mirror steering. In this case the range of mirror steering remains the same as it was described above with the following equation $\Delta\sigma_b = \pm R_a / 2 Z_n$.

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Fig. 6 shows another autocollimative/reflective optical switch 600 based on a focusing Angle-To-Offset Mirror (ATOM). Its operation is similar to the optical switch 200 described in conjunction with Fig. 3. However, switch 600 employs a MEMS chip 614 having a micro-mirror arrangement thereon for directing the beam to a respective deflection point on the ATOM 616. Aside from the ATOM 616, switch 600 has a waveguide bundle 610, a projective lens 612, and a MEMS chip 614. Again, it is advantageous to use a telecentric magnifier for the projective lens 612. Input waveguides and output waveguides are mixed together in waveguide bundle 610 and hence, the port count of optical switch 600 is reduced by a factor of 2. In accordance with this embodiment of the invention, the micro-mirrors on the MEMS chip comprise the micro-mirrors dedicated for directing the input signals as well as the output signals. The layout of the micro-mirrors on the MEMS chip 614 depends on the assignment of the input port or ports and the output ports on the waveguide bundle 610, i.e. whether they are sectioned in groups or interlaced, for example.

Figs. 7 to 11 illustrate further design considerations for optical switches in accordance with the present invention. The number of ports is defined by the imaging lens, the size of the MEMS chip, and the ATO lens or mirror. The number of ports that can be accommodated in the optical system is directly proportional to the size of the MEMS chip, inversely proportional to the F/#, and proportional to the square of the optical filling factor. Thus, in order to maximize the port count, it is most efficient to maximize the optical filling factor.

The optical filling factor is defined as follows $K_f = D_b / D_i$, where D_b is the beam diameter and D_i is the distance between the axes of two closest beams. Since the diameter of a standard single-mode fiber is 125 μm and its mode field diameter is ~15μm, which is defined at the level 3ω, the filling factor of the waveguide bundle can not be higher than 0.12. This optical filling factor is not effected by the magnification through the magnifying lens at the MEMS chip. However, below some techniques are described that can be used to increase the filling factor.

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A first technique for increasing the filling factor is to place an array of micro-lenses on top of the waveguide bundle end-face; one micro-lens centered on the optical axis of each waveguide. Such micro-lenses increase the beam diameter but not the distance between the beam axes and thereby directly improve the filling factor.

Fig. 7 demonstrates a second technique for increasing the filling factor which is to draw the fiber bundle under high temperature. The drawing diminishes the size of the bundle cross-section keeping geometrical similarity of original and drawn cross-sections. The drawing factor is defined as $K_d = D_d / D_b$, where D_b is the bundle diameter of the original bundle, and D_d is its diameter after drawing.

The distance between fiber axes diminishes and so does the fiber core diameter. The mode field radius ω dependence on step-index single-mode fiber core diameter is given by Marcuse's formula:

$$\omega = D\,(0.65 + 1.619\,V^{-1.5} + 2.879\,V^{-6})\,/2$$

where normalized frequency $V = D\pi\sqrt{n_1^2 - n_2^2}/\lambda$, n_1 and n_2 are refractive indexes of the fiber core and cladding, and D is the fiber core diameter. A mode field radius dependence on the drawing factor K_d for SMF-28 single-mode fiber is calculated according to this formula and this dependence is presented in Fig. 8, together with the filling factor dependence.

Looking at the graph presented in Fig. 8 from right to left, it is seen that the mode diameter remains approximately the same down to a drawing factor ~ 0.85, and then increases, while the filling factor increases monotonically as a function of the drawing factor.

A third possible technique for increasing the filling factor is to use a so-called "parallel projection" where several waveguide bundles, e.g.910 and 920, and associated projecting lenses 915 and 925 image the inputs from several locations for each MEMS chip 930. Such a "parallel projection is shown in Fig. 9, which is a modification of the system

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presented in Fig. 6, i.e. the reflective configuration. A similar modification can be done with the system presented in Fig. 5, i.e. the transmissive configuration.

In this parallel projection scheme, there are four sub-systems consisting of waveguide bundles 910 and 920 and projecting lenses 915 and 925 placed around an ATOLL (not shown) or an ATOM 940. Each of these sub-systems projects the light from its corresponding waveguide bundle 910 and 920, respectively, onto the same MEMS chip 930. Each image is oriented such that it is shifted relatively from its neighbour by half a pitch in one of the possible directions, see Fig. 10. Such a honeycomb structure can be used for the placement of waveguides and micro-mirrors of MEMS chips, as it provides the most compact positioning and the biggest number of connected channels.

With the parallel projection scheme shown in Fig. 9, the filling factor is increased two times. If nine parallel sub-systems are placed around the ATO mirror 940 or ATO lens (not shown), the filling factor is increased 3 times; by using 16 systems, the filling factor is increased 4 times and so forth.

Using this technique implies requirements for increased steering range of micro-mirrors, since they should compensate the angle between optical axes of projecting systems and the axis of the ATOLL or ATOM.

It is apparent that such a configuration lends itself as an example of how this system is built modularly, growing in port counts as desired or required by the customer.

A fourth possible technique to improve the filling factor is to etch away some of the cladding of the fibers.

As illustrated above, it is necessary to clock the MEMS chip with respect to the optical axis of the imaging lens. This is necessary to deflect the beams to propagate down the optical axis of the ATO lens or mirror. As a result of this, not all of the micro-mirrors are positioned at the image plane of the imaging system. Although this does not constitute a

theoretical problem, there could be practical issues associated with this, such as skew rays or missing micro-mirrors. In this case, larger micro-mirrors are necessary to capture the converging or diverging beams, for example.

In order to prevent this problem, an alternate optical scheme 1100 is presented in Fig. 11 in a transmissive configuration, wherein the telecentric imaging lens 1110 is itself not axially co-linear. The ATOLL is denoted with 1125 and the output waveguides are denoted with 1115. With this scheme, it is seen that the images of each input waveguide 1105 are co-planar with the MEMS chip 1120. However, if desired, this scheme is designed in reflection. Optical system 1100 requires greater care in the design of the off-axes lenses in order to avoid problems with aberrations of the lenses.

Numerous other embodiments can be envisaged without departing from the spirit and scope of the invention.

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In an ATO based large optical cross-connect, the routing table can be calculated based on the ATO surfaces profile and position. If the surface profile is simple (ie for example spherical) and will not change during operation, then the routing table of the switch during operation only depends on a reduced number of parameters, like:

- focal length of the ATO (f)
- position of the optical center of the ATO (x, y, z)
- orientation of the optical axis (θ_x, θ_y)

This reduced set of 6 parameters can be monitored in real-time to readjust the entire switch routing table during operation.

This set of parameters can be measured through some special calibration connections, different from the switching routes (for example, through adding a couple of actuators / detectors on the periphery of the 2D actuators array). These measurement results would be used to feed-back the calculated routing table for the entire switch.

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The calibration pixels could use quad detectors to provide a feed-back signal, and/or use frequency dithering and lock-in detection.

There could be more than 6 calibration connection and there could be more than 6 parameters required to fully characterize the ATO.

<u>Claim:</u>

A control method for an ATO switch in which selected calibration connections are used to measure the optical characteristics of the ATO element in real time and use this information to compute the routing table for the switch.

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Claims

What is claimed is:

1. An optical switch comprising:

(a) an input port for launching a beam of light into the optical switch;

(b) a plurality of output ports, each output port for selectively receiving the beam of light;

(c) an element having optical power and a focal length approximately equal to a near zone length for providing an angle to offset transformation; and

(d) beam directing means for selectively directing the beam of light from the input port to any one of the plurality of output ports along an optical path via the element having optical power.

2. The optical switch as defined in claim 1 wherein the element having optical power is for maintaining a radius of the beam of light.

3. The optical switch as defined in claim 1 wherein the element having optical power has a first and a second focal plane.

4. The optical switch as defined in claim 3 wherein a waist of the beam is substantially the same in the first focal plane and the second focal plane.

5. The optical switch as defined in claim 3 wherein a divergence of the beam is substantially the same in the first focal plane and the second focal plane.

6. The optical switch as defined in claim 4 wherein the focal length of the element having optical power is proportional to a square of the waist of the beam of light.

7. The optical switch as defined in claim 3 wherein the element having optical power is a curved mirror.

8. The optical switch as defined in claim 7 wherein the first and the second focal plane is a substantially same focal plane.

9. The optical switch as defined in claim 3 wherein the element having optical power is a lens.

10. The optical switch as defined in claim 9 wherein the first focal plane is a front focal plane in front of the lens and the second focal plane is a back focal plane behind the lens along the optical path.

11. The optical switch as defined in claim 7 wherein the input port and the plurality of output ports are disposed adjacent to one another.

12. The optical switch as defined in claim 11 wherein the beam directing means are adjacent to the input port.

13. The optical switch as defined in claim 12 wherein the beam directing means is an arrangement of two mirrors.

14. The optical switch as defined in claim 12 wherein the beam directing means is a MEMS device for changing an axis of an optical cone of the beam launched into the optical switch at the input port.

15. The optical switch as defined in claim 14 wherein the MEMS device includes an x-y positioner for positioning a waveguide at the input port.

16. The optical switch as defined in claim 15 wherein the x-y positioner is one of a comb drive and a thermal drive.

17. The optical switch as defined in claim 11 wherein the beam directing means is an array of micro-mirrors on a MEMS chip being optically coupled with the input port and any one of the plurality of output ports.

18. The optical switch as defined in claim 3 wherein the beam directing means include a first array of micro-mirrors on a first MEMS chip at the first focal plane and a second array of micro-mirrors on a second MEMS chip at the second focal plane.

19. The optical switch as defined in claim 9 wherein the beam directing means include a first array of micro-mirrors on a first MEMS chip at the front focal plane of the lens and a second array of micro-mirrors on a second MEMS chip at the back focal plane of the lens, the first and the second array of micro-mirrors being disposed along an optical path between the input port and the plurality of output ports.

20. The optical switch as defined in claim 19 wherein the first array of micro-mirrors is for tilting the beam of light, said tilt being converted to a lateral displacement using the lens and imaged onto the second array of micro-mirrors for selectively redirecting the beam to any one of the plurality of output ports.

21. The optical switch as defined in claim 9 further including a lens for imaging the beam of light onto the beam directing means.

22. The optical switch as defined in claim 21 wherein the lens is a telecentric lens system.

23. The optical switch as defined in claim 1 further including a micro-lens centered on an optical axis of the input port for increasing a beam diameter of the beam of light.

24. The optical switch as defined in claim 22 wherein the telecentric lens system is an off-axis telecentric imaging system.

25. An optical switch comprising:

(a) an input port for launching a beam of light into the optical switch;

(b) a plurality of output ports, each output port for selectively receiving the beam of light;

(c) an element having optical power and a focal length approximately equal to a Raleigh range for providing an angle to offset transformation; and

(d) beam directing means for selectively directing the beam of light from the input port to any one of the plurality of output ports along an optical path via the element having optical power.

26. The optical switch as defined in claim 25 wherein the beam is being directed in a transmissive or reflective configuration.

27. The optical switch as defined in claim 25 wherein the element having optical power is a lens.

28. The optical switch as defined in claim 25 wherein the element having optical power is a curved mirror.

29. An optical switch comprising an array of controllable deflecting elements for deflecting a beam of light and an optical element having power optically coupled with the array of deflecting elements whose focal length is approximately equal to the Raleigh range of the beam being deflected.

30. The optical switch as defined in claim 29 wherein the element having power is a lens.

31. The optical switch as defined in claim 29 wherein the element having power is a curved mirror.

32. The optical switch as defined in claim 29 further comprising a plurality of waveguides having ends serving as ports optically coupled with the array of controllable deflecting elements.

33. The optical switch as defined in claim 32 further comprising a second plurality of waveguides having ends serving as ports optically coupled with the array of controllable deflecting elements, and wherein the optical element having power is a lens.

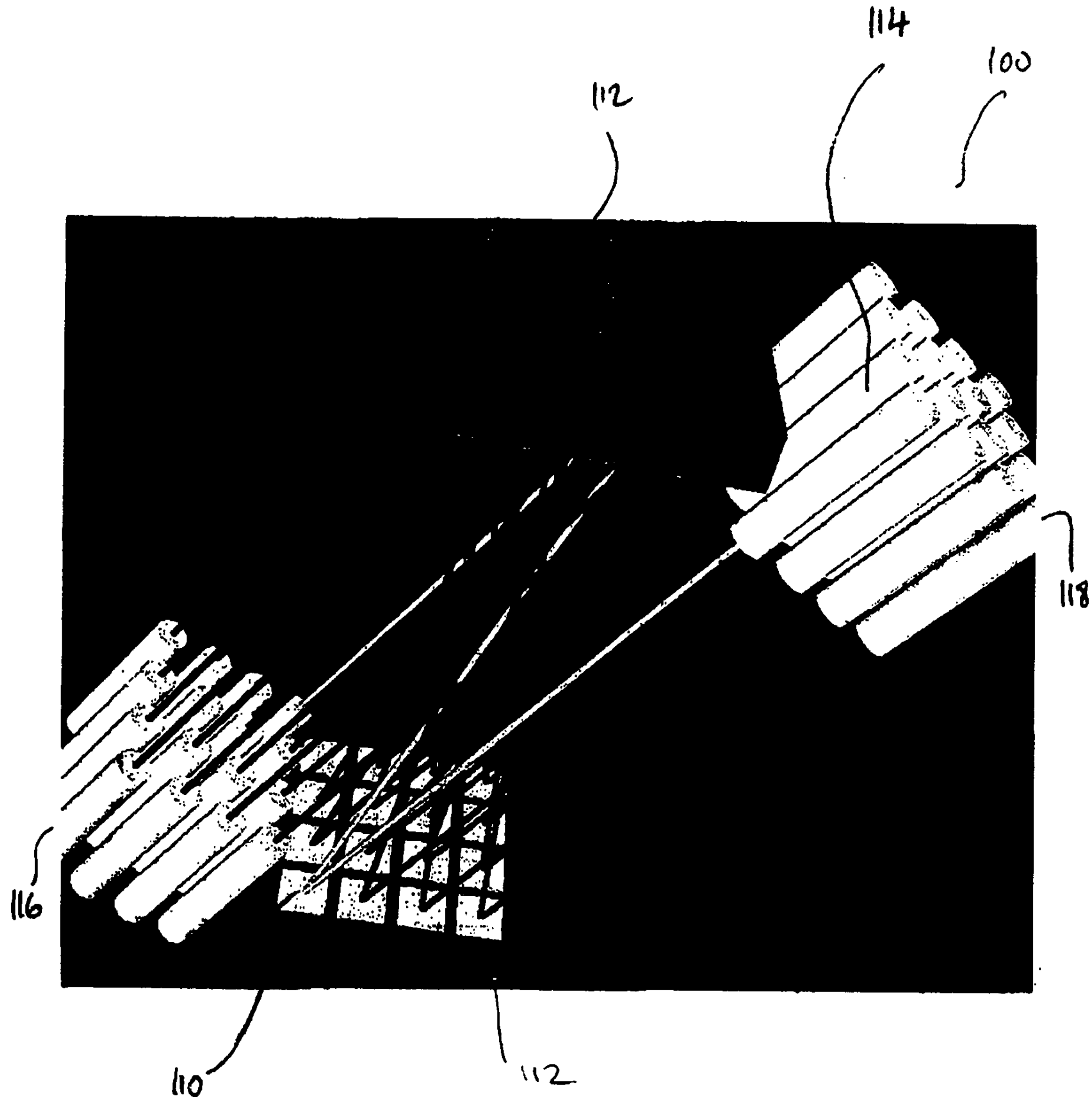


Fig. 1 (PRIOR ART)

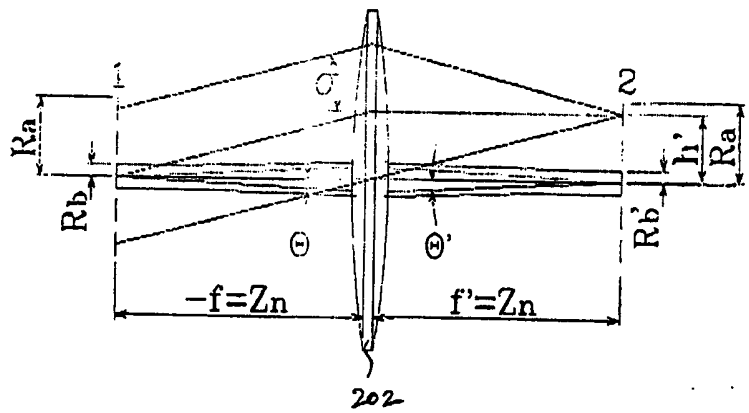


Fig. 2

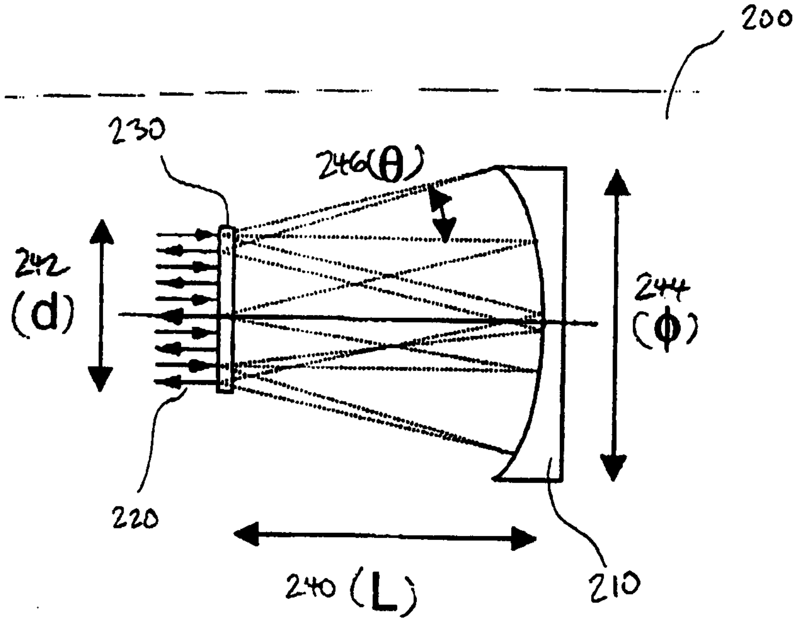
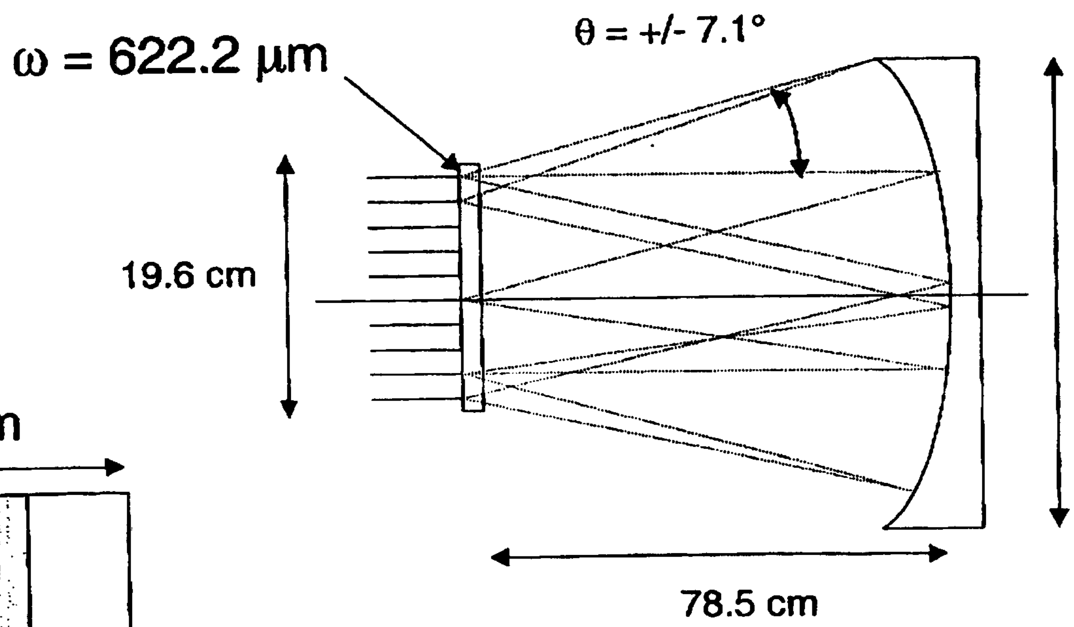
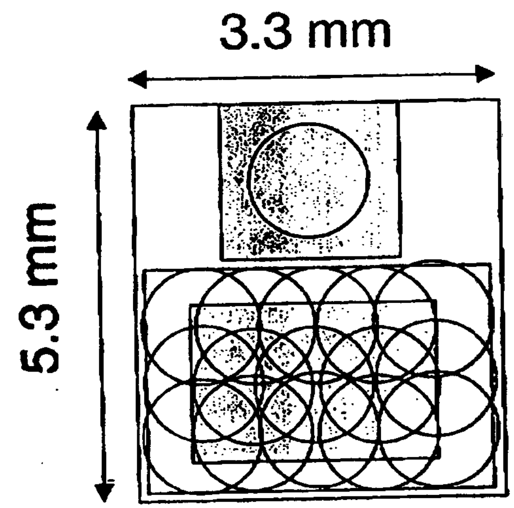


Fig. 3

Example 2: "Astarte-like" 576 x 576 1D + 1D mirrors

K=20%, F#=2



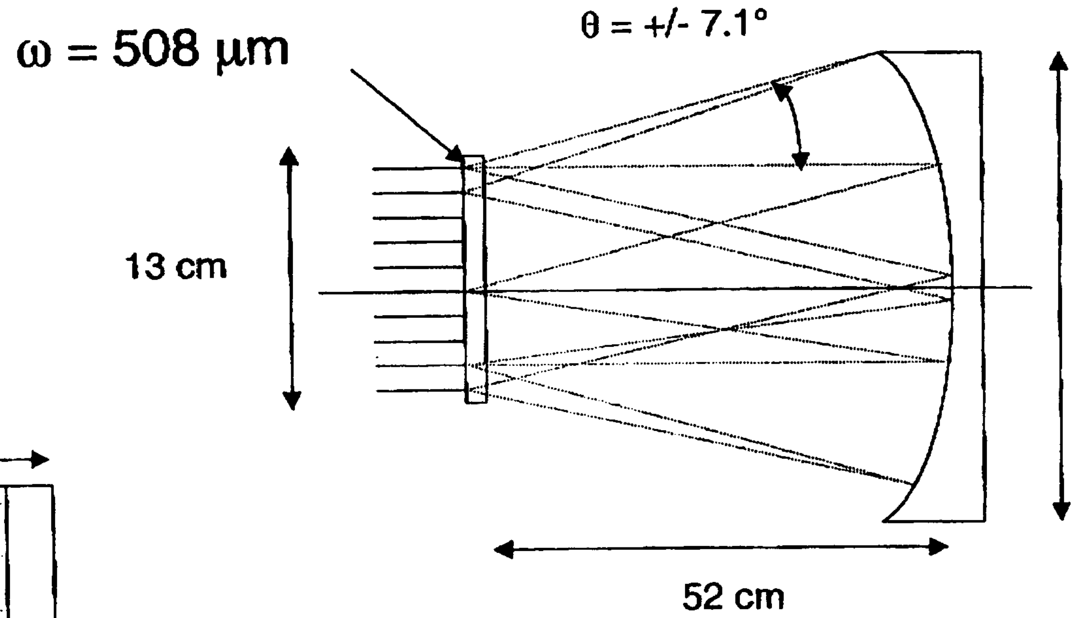


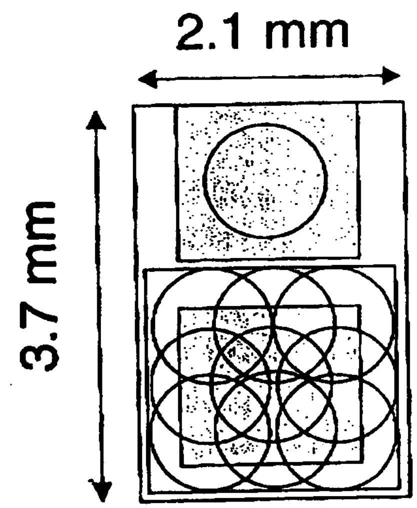
Projected dimensions:
1st mirror = 1.87 x 1.87 mm2, horizontal deflection
2nd mirror = 3.19 x 1.87 mm2, vertical deflection
beam ϕ = 1.24 mm @ 2ω

Fig. 3a

Example 2: "Astarte-like" 576 x 576 2D mirrors

K=30%, F#=2





<u>Projected dimensions:</u>
1st mirror = 1.52 x 1.52 mm2, fixed mirror
2nd mirror = 1.52 x 1.52 mm2, 2D deflection
beam ϕ = 1.02 mm @ 2ω

Fig. 3b

Example 1: compact 1024 x 1024 switch

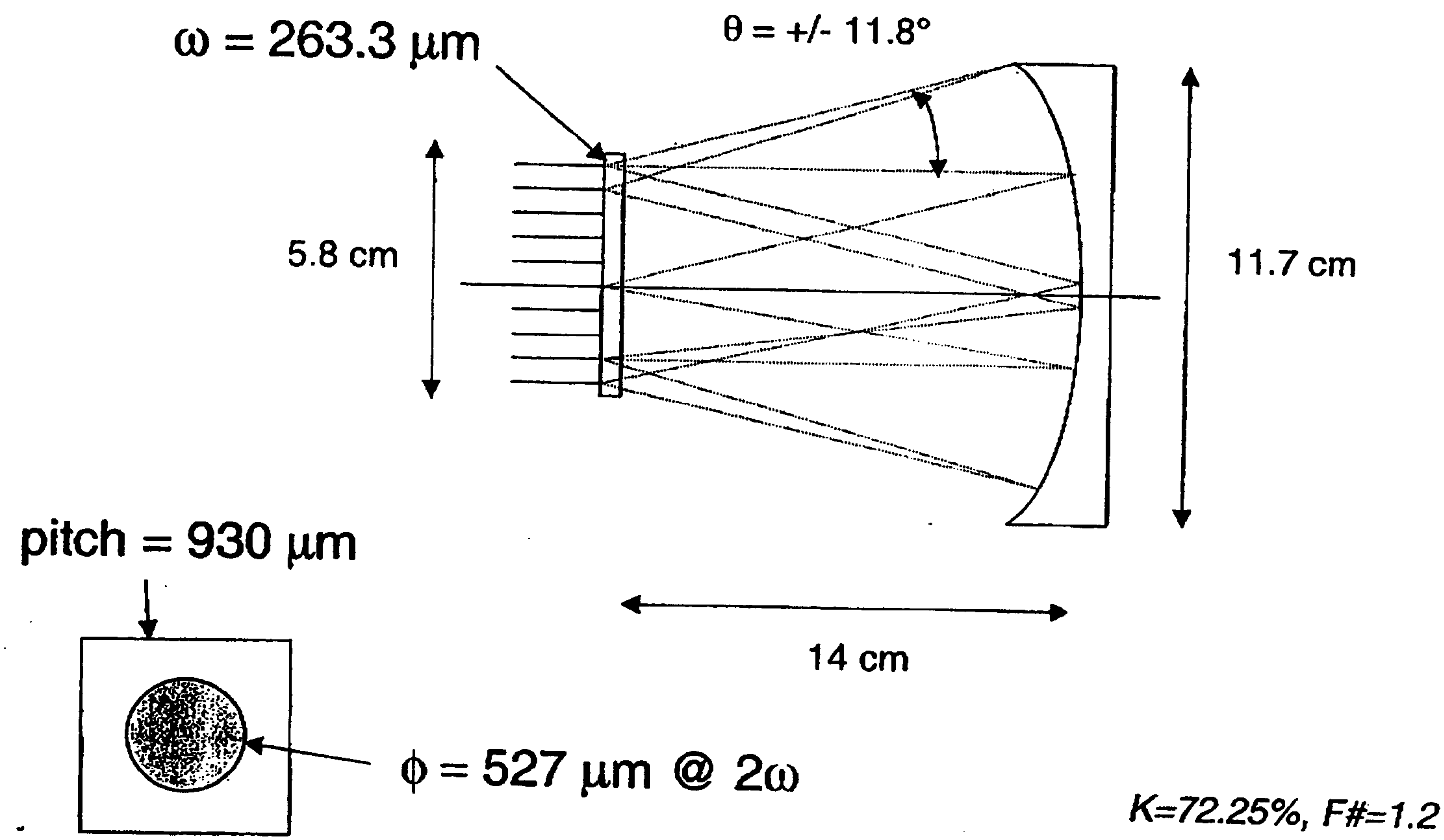


Fig. 3c

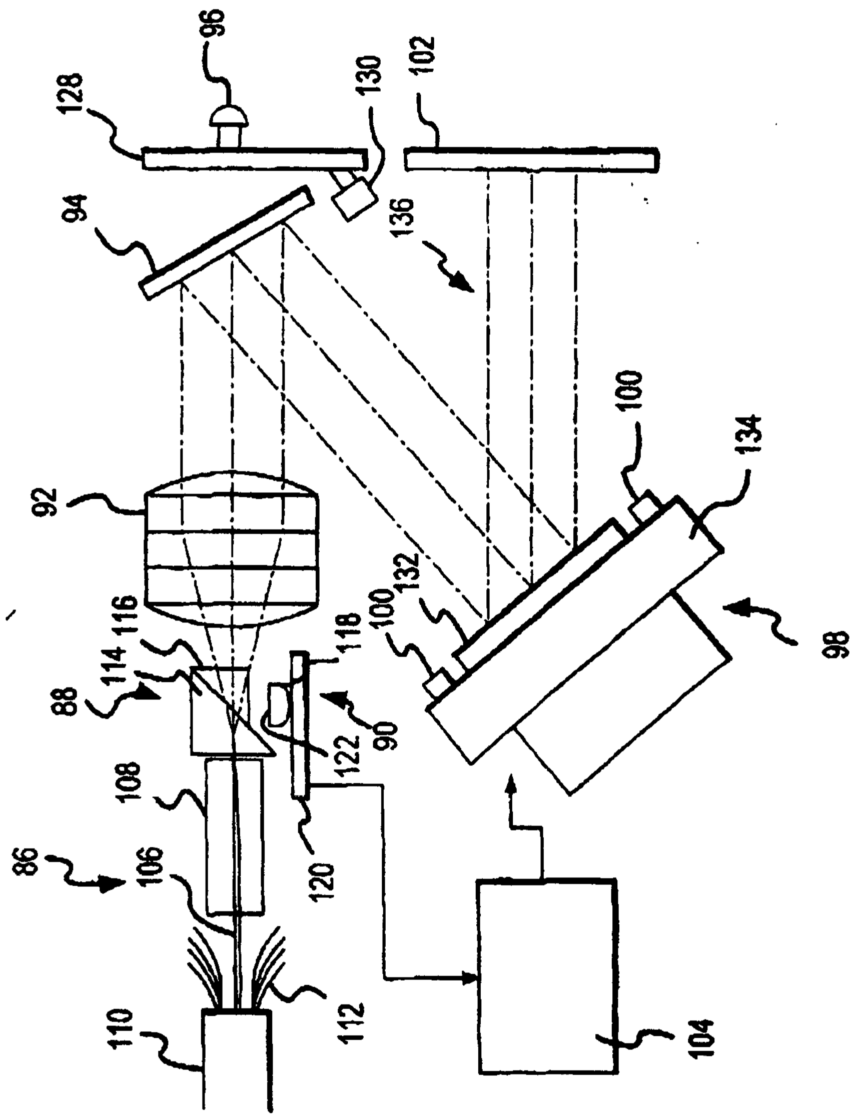

96
128
130
102
94
136
100
134
92
116
114
88
132
100
118
90
122
108
86
106
120
98
110
112
104

Fig. 3d

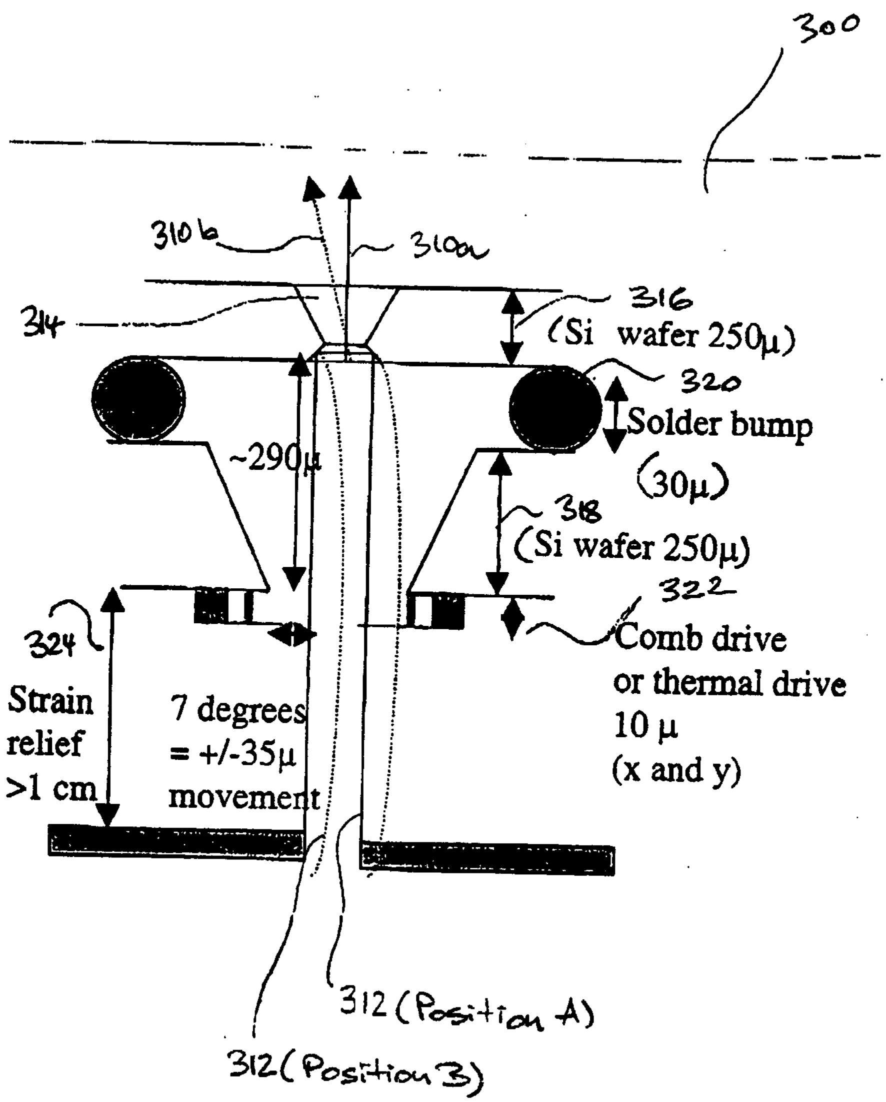

300
310b
310a
314
316
(Si wafer 250µ)
320
Solder bump
(30µ)
~290µ
318
(Si wafer 250µ)
322
Comb drive
or thermal drive
10 µ
(x and y)
324
Strain
relief
>1 cm
7 degrees
= +/-35µ
movement
312 (Position A)
312 (Position B)

Fig. 4

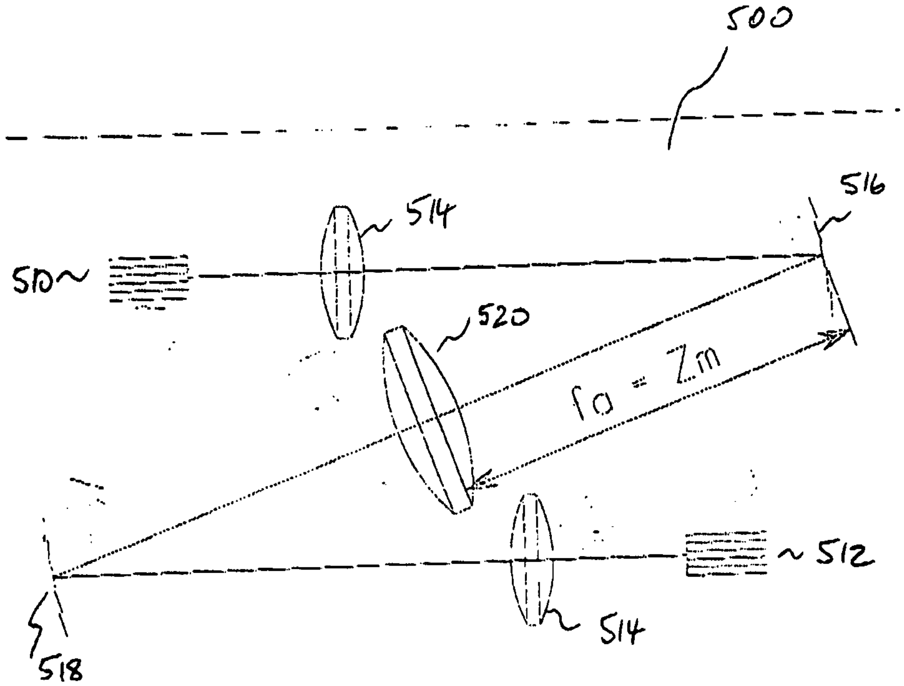


Fig. 5

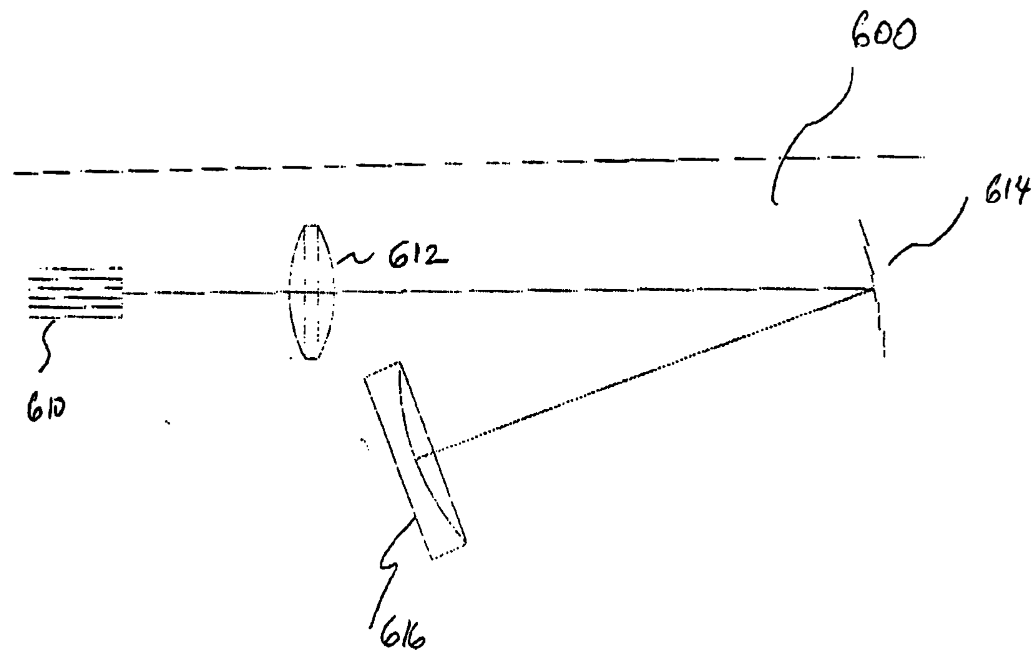


Fig. 6

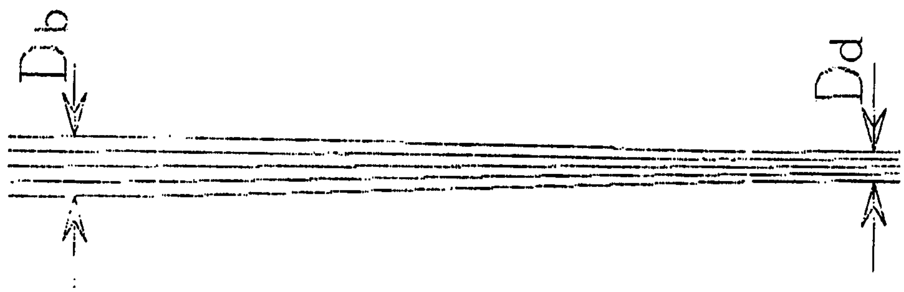

Db
Dd

Fig. 7

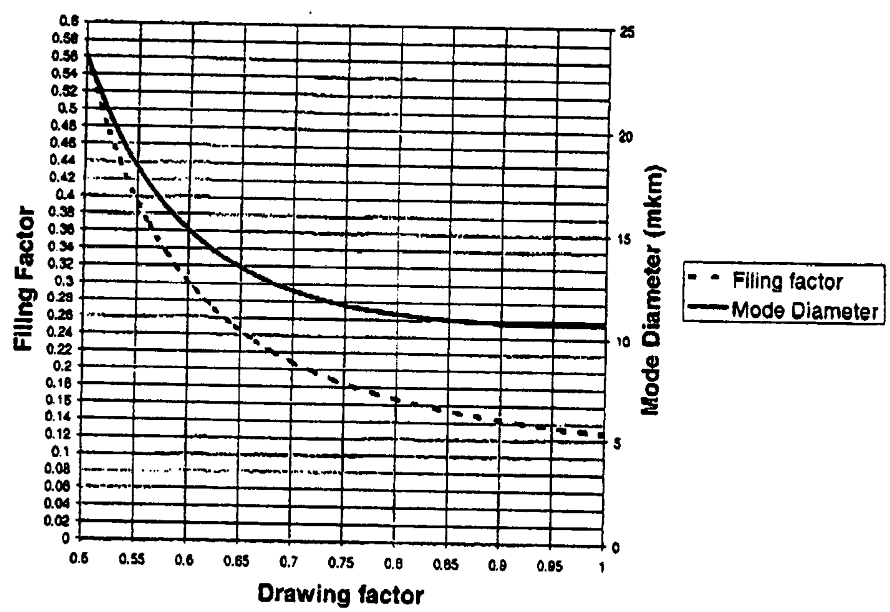

Filing Factor
Mode Diameter (mkm)
Drawing factor
Filing factor
Mode Diameter

Fig. 8

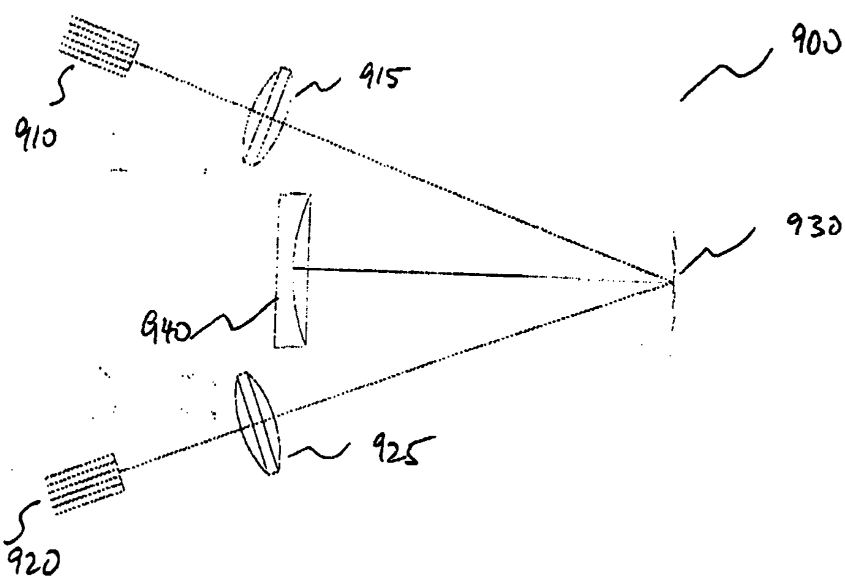

900
915
910
930
940
925
920

Fig. 9

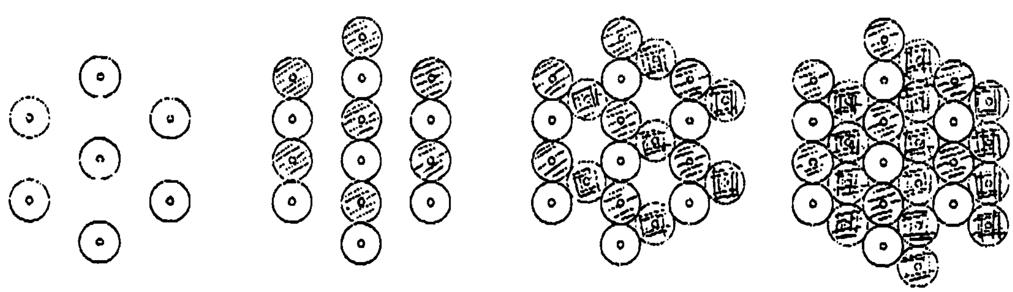


Image 1
Image 1+2
Image 1+2+3
Image 1+2+3+4

Fig. 10

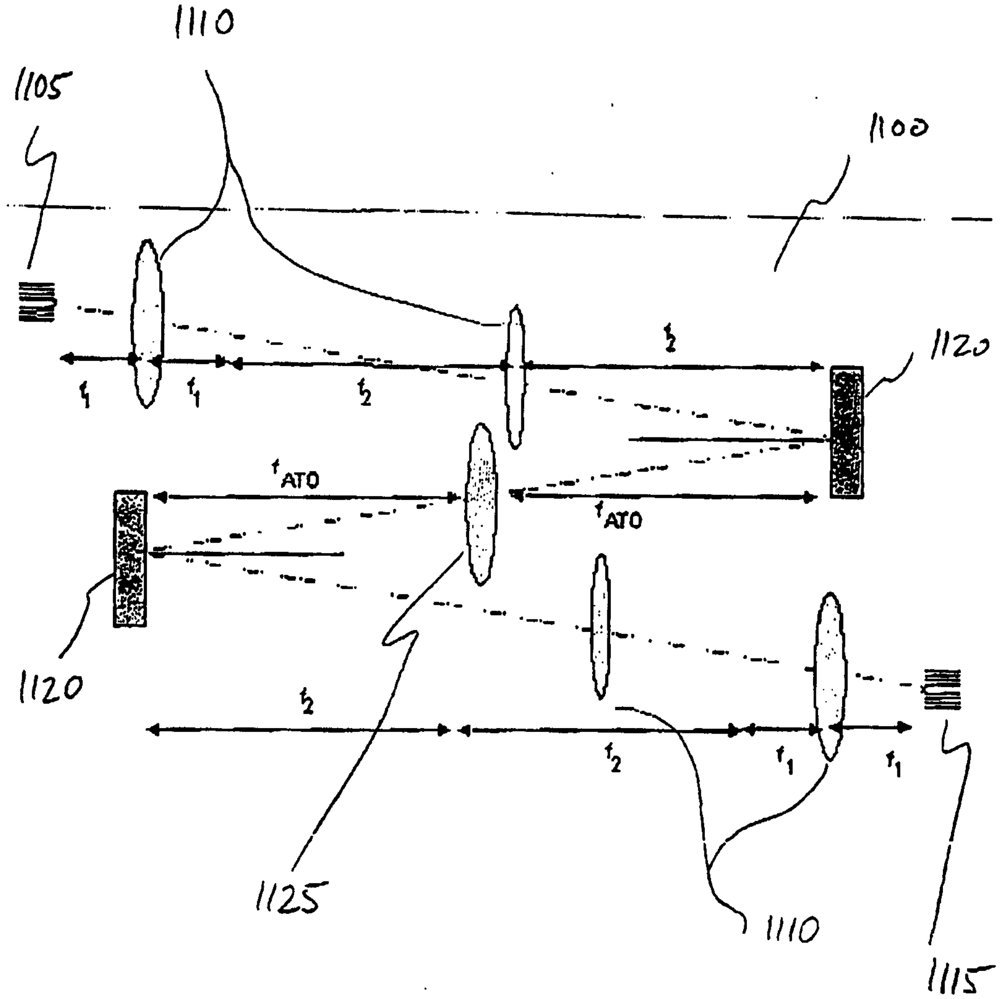

1110
1105
1100
f_2
1120
f_1
f_1
f_2
f_{ATO}
f_{ATO}
1120
f_2
f_2
f_1
f_1
1125
1110
1115

Fig. 11